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Radio frequency heating: a potential method for post-harvest pest control in nuts and dry products

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Abstract: The multi-billion dollar US tree nut industries rely heavily on methyl bromide fumigation for postharvest insect control and are facing a major challenge with the mandated cessation by 2005 of its use for most applications. There is an urgent need to develop effective and economically viable alternative treatments to replace current phytosanitary and quarantine practices in order to maintain the competitiveness of US agriculture in domestic and international markets. With the reliable heating block system, the thermal death kinetics for fifth-instar codling moth, Indianmeal moth, and navel orangeworm were determined at a heating rate of 18 °C/min. A practical process protocol was developed to control the most heat resistant insect pest, fifth-instar navel orangeworm, in in-shell walnuts using a 27 MHz pilot scale radio frequency (RF) system. RF heating to 55 °C and holding in hot air for at least 5 min resulted in 100% mortality of the fifth-instar navel orangeworm. Rancidity, sensory qualities and shell characteristics were not affected by the treatments. If this method can be economically integrated into the handling process, it should have excellent potential as a disinfestation method for in-shell walnuts.

Keywords: Disinfestation, Heat, Nut, Postharvest, Radio frequency
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NEED TO REPLACE CHEMICAL FUMIGANTS FOR PEST CONTROL

For years, researchers have searched for alternative methods to disinfest post-harvest commodities without using chemical fumigants. The need to replace those compounds becomes more urgent as the public becomes more aware of their negative impact on human health and environment. Methyl bromide (MeBr) is used extensively on a global basis as a fumigant against nematodes, weeds, insects, fungi, bacteria, and rodents. Commodities that use this material as part of a post-harvest pest control regime include grains, nuts, fresh and dried fruits, forestry products, and imported materials. When used for commodity fumigation, MeBr gas is injected into a chamber or under a tarp containing the commodities. About 80% to 95% of the MeBr used for a typical commodity treatment eventually enters the atmosphere. MeBr was listed as an ozone depleting substance in 1992 at the 4th Meeting of the Parties to the Montreal Protocol on Substances that deplete the ozone layer. Developed countries were required to freeze production and importation of MeBr in 1994 at the 1991 levels and to reduce the use by 25% in 1999, 50% in 2001, 70% in 2003, and 100% in 2005. Developing countries were required to freeze consumption and production of MeBr in 2002, reduce it by 20% in 2005 and phase it out by 2015 (USEPA, 2001). Although exemptions exist for postharvest quarantine treatments under both the

US Clean Air Act and the Montreal Protocol, it is expected that MeBr will become more expensive and difficult to acquire.

RADIO FREQUENCY HEATING AS A POTENTIAL METHOD

In recent years, conventional thermal treatment methods using hot water or hot air were investigated as an alternative to MeBr fumigation for a number of commodities and pests. Varying degrees of efficacy of various thermal treatments alone or in combination with cold or controlled atmosphere storage conditions had been reported (Wang and Tang, 2001). Since many insect pest larvae can bore into the center of fruits, nuts, seeds or kernels, the center of the commodity must be heated to lethal temperatures. Prolonged heating may be detrimental to the quality of treated products, and may not be practical in industrial applications (Lurie, 1998).

The problem of commodity intolerance to slow, non-uniform heating under conventional methods may be solved by heating with radio frequency (RF) and microwave (MW) energies. This electromagnetic energy interacts directly with the commodity's interior to quickly raise the center temperature (Tang *et al*., 2000; Wang *et al*., 2001a; 2001b). Early research efforts using RF and MW energy for insect control were, however, generally hindered by the availability and acceptance of comparatively inexpensive chemical fumigants (Nelson, 1996). The cost of RF and MW equipment has decreased to a level comparable to that of conventional heating equipment, and the need for alternatives to chemical fumigation has become very urgent. Both renewed the interests in exploring the use of RF and MW energy in pest control applications.

RF and MW treatments involve the application of electromagnetic energy at 10 MHz to 30 000 MHz. The Federal Communications Commissions (FCC) has allocated five frequencies for industrial, scientific, and medical (ISM) in the USA. The frequencies for RF are 13.56 MHz, 27.12 MHz and 40.68 MHz; and those for MW are 915 MHz and 2450 MHz. RF and MW energies leave no residues on products and no chemicals to dispose of. During the treatments, RF and MW energies are confined in metal tunnels, and the treatment systems are designed to permit leakage much smaller than the signal for cellular telephones. In this way, the processes are safe to operators and have no impact on the environment. RF energy has larger penetration depth in fresh fruits and nuts because its wavelength is much longer wavelength than that of MW (Wang *et al*., 2003b). In addition, the dielectric loss factor of insect pests in the RF region is larger than that of the host dry products, which may lead to preferential heating of insects. For those reasons, we have chosen to use RF energy in our development efforts.

CURRENT DEVELOPMENTS

Strategies

Extensive research and development efforts were launched in 2000 by a multi-disciplinary team of researchers in engineering, entomology and plant physiology led by Washington State University (WSU) and supported by various programs including USDA IFAFS, IREECGP and NRI programs, and Californian Walnut Marketing Board. The researchers are affiliated with WSU, University of California at Davis (CA), and USDA research stations in Wenatchee (WA), Wapato (WA), Parlier (CA), and Weslaco (TX). An important key in developing successful thermal treatments is to balance complete kill of insects with minimized thermal impact on product quality. The thermal treatment protocols' effectiveness rests on: 1) knowledge of the thermal resistance of the targeted insects; 2) proper engineering of thermal energy delivery methods; 3) understanding of the thermal effects on product quality; 4) applying pilot-scale results to large-scale industry treatments.

Progresses

(1) Heating block system

At the start of the project, the information on true thermal tolerance of insect pests for the conditions suited for developing rapid and effective treatment processes was not available in the literature. A major challenge was to develop a unified approach to study heat tolerance of quarantined insects that cannot be transported live across state or country boundary lines. For this purpose, a unique heating block system was developed at WSU that directly exposes insect pest to a heated environment at controlled heating rates (Wang *et al.*, 2002b). The system consists of a top and bottom aluminum block, heating pads, insect chamber, controlled atmosphere circulating channel, and a data acquisition/control unit (Fig.1). The insect chamber formed by the cavity of the two blocks can hold up to 200 insects per run.

This system is able to precisely ramp the temperature in the insect test chamber at a controlled rate from 0.1 to 20 °C/min. The thermal capacitance of the blocks provides smooth temperature profiles over the heating and holding periods. Calibrated type-T thermocouples, inserted through sensor holes near the center of each block, are used to monitor the temperatures of the top and bottom blocks. The block temperature is controlled by PID controllers (I32, Omega Engineering, Inc., Stamford, CT) to increase linearly to within ±0.3 °C of the desired set point (Fig.2). This system is now used in several laboratories in the US and in Israel to study thermal susceptibility of important insects such as codling moth (*Cydia pomonella*), navel orangeworm (*Amyelois transitella*), Indianmeal moth (*Plodia interpunctella*), Mediterranean (*Ceratitis capitata*) and Mexican fruits flies (*Anastrepha ludens*), apple maggot (*Rhagoletis pomenella*), and red flour beetle (*Tribolium castaneum*) (Wang *et al.*, 2002a; 2002b; Johnson *et al.*, 2003; Gazit *et al.*, 2004).

(2) Thermal death kinetics of targeted insects

The thermal death time (TDT) curves for codling moth, navel orangeworm, and Indianmeal moth that are most important insect pests in walnuts are included in Fig.3. The results suggest that navel orangeworm is the most heat resistant insect at the fifth-instar life stage. A complete kill of 600 fifth-instar navel orangeworms requires minimum exposures of 140, 50, 15, 6 and 1 min at 46, 48, 50, 52 and 54 °C, respectively.

The activation energy for thermal inactivation of fifth-instar navel orangeworm, Indianmeal moth and codling moth are 519, 506 and 472 kJ/mol, respectively. In general, the activation energy for thermal kill of insects is slightly greater than that for thermal inactivation of pathogenic microbial spores (210−350 kJ/mol) and much greater than for softening and many other quality changes (42−126 kJ/mol) in food commodities due to heat. That is, insect pests are more sensitive to increase in treatment temperatures than most fruit quality aspects. This provides opportunity for the possible development of relatively high-temperature-short-time thermal treatment processes that may kill insects while having minimal impact on product quality.

(3) Differential heating of insects in nuts

A benefit of using RF energy to control insect

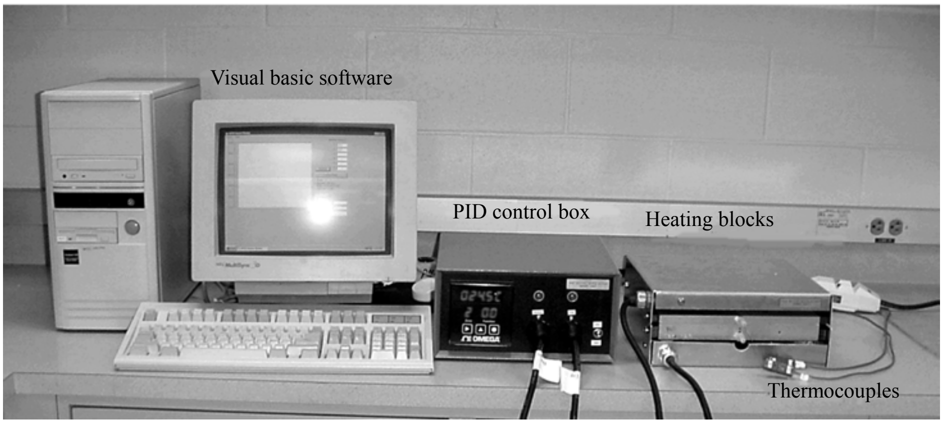

Fig.1 WSU heating block system for insect mortality studies

pests is that the insects may be heated at a faster rate than the product they infest. We may be able to develop treatments that allow insect pests to be heated to a lethal temperature while maintaining product temperature below the quality limit. For the first time in the history of insect control research, we have theoretically and experimentally proved that it is possible to preferentially heat insects in nut products. With fiber-optic sensors, we measured from 5 °C to 10 °C higher temperatures in fifth-instar codling moth than in the host walnut kernels after 3 min heating with RF energy at 27.12 MHz to a final walnut temperature of 50 °C (Fig.4, Wang *et al*., 2003a). This means that we can selectively heat and kill insect pests at a lower nut temperature, thereby reducing treatment time and increasing product throughput. The degree of preferential heating of insects may be different in other nuts and fruits, but the results are very encouraging and can be used for developing effective insect control treatments.

(4) RF protocols for in-shell walnuts

A 6 kW, 27 MHz pilot-scale RF system (COMBI 6-S, Strayfield International Limited, Workingham, UK) was used to develop a process protocol to control insect pests in in-shall walnuts. Walnuts were infested with the most heat resistant life stage (fifth-instars) of navel orangeworms at USDA-ARS in Parlier, CA. An insect larva was placed in each walnut through a pre-drilled hole in the shell. The hole was sealed with a gum to prevent insects from escaping from the walnuts. Infested walnuts were shipped by overnight delivery to WSU for RF treatments. Three different process protocols were selected based on the thermal mortality of insects in walnuts and the thermal effects on walnut quality. The RF heating of walnuts 55 °C and holding them in hot air for more than 5 min resulted in 100% mortality of the fifth-instar navel orangeworm (Wang *et al*., 2002c).

Walnuts contain high concentrations of polyunsaturated fatty acids. This makes them susceptible to the development of oxidative and hydrolytic rancidity, especially at high temperatures. The two main parameters indicating walnut oxidative rancidity are peroxide value (PV, meq/kg) and fatty acid (FA, % oleic). According to the industry standard (Diamond Walnut Company, Stockton, CA), good quality walnuts should have a PV<1.0 meq/kg and an FA<0.6%. Table 1 shows that the final PV and FA values during accelerated storage of up to 20 d

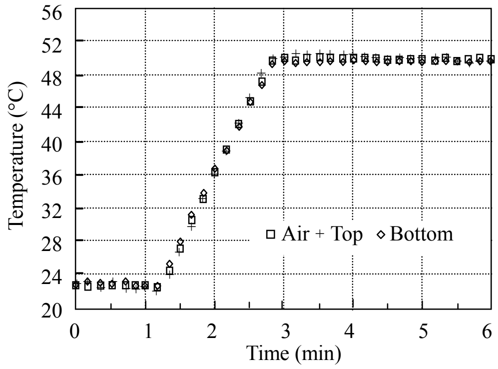

Fig.2 Air, top and bottom plate temperatures of the heating block system when heated to 50 °C at a rate of 18 °C/min

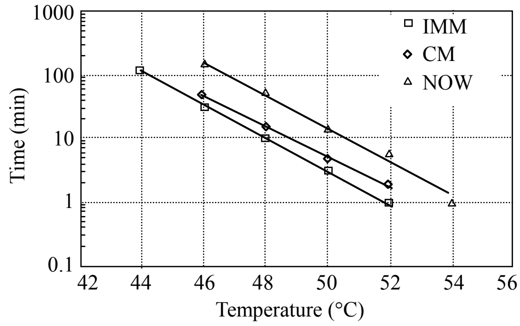

Fig.3 Thermal-death-time (TDT) curve for 600 fifth-instar Indianmeal moth (IMM), codling moth (CM) and navel orangeworm (NOW) at a heating rate of 18 °C/min

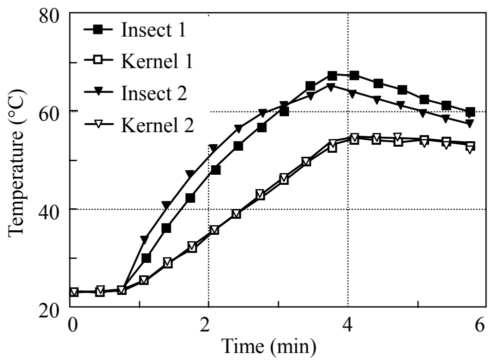

Fig.4 Typical temperature profiles of walnut kernels and codling moth slurry when subjected to 27 MHz RF heating (Wang *et al.*, 2003a)

Table 1 Chemical characteristics of in-shell walnuts treated by RF energy

Storage time at 35 °C (day)	Peroxide value* (meq/kg)		Fatty acid (%)	
	Control	RF with hot air+10 min	Control	RF with hot air+10 min
0	0.01±0.01	0.02±0.01	0.10±0.01	0.10±0.02
10	0.28±0.11	0.18±0.12	0.15±0.01	0.15±0.01
20	0.64±0.16	0.61±0.03	0.21±0.01	0.17±0.03

*Accepted PV and FA values for good quality are less than 1.0 meq/kg and 0.6%, respectively

after RF treatments remained lower than the industry standard values (PV<1.0 meq/kg and FA<0.6%) for good walnut quality. Rancidity, sensory qualities and shell characteristics were not affected by the treatments. The process slightly reduced the moisture content of the walnut kernels, which could prove an additional benefit by providing even nut moisture content and reducing the growth of microorganisms. If this method can be economically integrated into the handling process, it should have excellent potential as a disinfestation method for in-shell walnuts.

FUTURE OUTLOOK

The short RF treatment time makes it possible to design continuous treatment processes to allow processing of large quantities of products in a short period of time, a tremendous advantage over batch-type fumigation or conventional heating. Continuous processes also reduce labor cost and use of space, and cause less mechanical damage to the commodities as a result of significantly reduced handling steps, as compared to traditional batch fumigation processes. RF can also be used together with other operations to reduce treatment time and modernize handling processes. For example, in-shell walnuts are currently fumigated by methyl bromide in tanks upon arrival at a storage facility or processing plant. The walnuts are then washed and dried in bins. These processes take 10–12 h, and walnuts are dropped into bins several times, which leads to cracking of shells. It is possible to combine RF treatment for control of insect pests with RF drying to reduce the whole process time to 15–20 min in a continuous process, thus significantly reducing process time, space, and quality loses.

The well-established commercial RF and MW operations for textile and wood drying may be extended for nut insect control. Over four hundred continuous industrial process lines have been in stalled in U.S. Such a technology can serve as a basis to design a continuous operation with conveyor belts transporting multi-layer products through an MW cavity or between two RF plate electrodes. Since the specific heat capacity of dry nuts and fruits is small (about 2 kJ/kg·K), the energy requirement for heating these products from room temperature to 55 °C will be relatively small (0.025 kW·h/kg). Typical RF and MW systems have an overall energy efficiency of 60% to 80%. The energy efficiency can be increased by using the waste heat from generators for concurrent surface heating of nuts to kill surface pests on the outside of the shell. Therefore, it is possible to provide the industry with an effective, rapid and environmentally friendly nut insect control process.

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